

RESEARCH ARTICLE

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Key Points:

- Out of 57 only a few urban areas showed increases in extreme rainfall
- RCMs show significant bias in extreme rainfall over urban areas
- Rainfall maxima is projected to increase in urban areas

Supporting Information:

- Readme
- Tables S1–S3 and Figures S1–S18

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Observed and projected urban extreme rainfall events in India

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Abstract We examine changes in extreme rainfall indices over 57 major urban areas in India under the observed (1901–2010) and projected future climate (2010–2060). Between 1901 and 2010, only four out of the total 57 urban areas showed a significant (p -value < 0.05) increasing trend in the monsoon maximum rainfall (MMR). Time-varying trends for the various rainfall indices exhibited that only a few urban areas experienced significant increases in the extreme rainfall indices for the different periods. Moreover, rainfall maxima for 1–10 day durations and at 100 year return period did not change significantly over the majority of urban areas in the post-1955 period. Results do not indicate any significant change ($p > 0.05$) in the pooled mean and distribution of the extreme rainfall indices for the pre- and post-1983 periods revealing an insignificant role of urbanization on rainfall extremes in the major urban areas in India. We find that at the majority of urban areas changes in the extreme rainfall indices are driven by large scale climate variability. Regional Climate Models (RCMs) that participated in the CORDEX-South Asia program showed a significant bias in the monsoon maximum rainfall and rainfall maxima at 100 year return period for the majority of urban areas. For instance, most of the models fail to simulate rainfall maxima within $\pm 10\%$ bias, which can be considered appropriate for a storm water design at many urban areas. Rainfall maxima at 1–3 day durations and 100 year return period is projected to increase significantly under the projected future climate at the majority of urban areas in India. The number of urban areas with significant increases in rainfall maxima under the projected future climate is far larger than the number of areas that experienced significant changes in the historic climate (1901–2010), which warrants a careful attention for urban storm water infrastructure planning and management.

1. Introduction

Climatic change poses a tremendous pressure on our society and environment [Peterson and Manton, 2008; Mishra et al., 2012]. Under a warming climate, rainfall extremes increase as shown by both observations and climate model simulations [Goswami et al., 2006; Kharin et al., 2007; Sun et al., 2007; Rajeevan et al., 2008; Revadekar et al., 2011; Mishra et al., 2012]. Rajeevan et al. [2008] and Goswami et al. [2006] reported that extreme rainfall events in India increase in the global warming, which is consistent with the findings of many previous studies [Kharin et al., 2007; O’Gorman and Schneider, 2009]. Min et al. [2011] argued that increases in extreme rainfall in the Northern hemisphere are directly associated with an anthropogenic driven rise in greenhouse gases. Water holding capacity of the atmosphere increases by about 6–7% per 1°C warming, which causes increases in extreme rainfall [Kharin et al., 2007; Trenberth, 2008]. Furthermore, sub-daily rainfall extremes are more sensitive than daily extremes to the climate warming [Lenderink and Van Meijgaard, 2008; Mishra et al., 2012].

An intensification of heavy precipitation events was observed over the Northern hemisphere land areas [Min et al., 2011]. In the USA, 30% of urban areas showed statistically significant increases in the indices related to extreme precipitation for the period of 1950–2009 [Mishra and Lettenmaier, 2011]. Increasing trends in precipitation extremes were observed in Europe [Wijngaard et al., 2003; Fowler and Ekström, 2009]. Goswami et al. [2006] reported a significant rising trend in frequency and magnitude of extreme rain events over the central India for the period of 1951–2000. However, Ghosh et al. [2012] found increases in spatial variability of extreme precipitation events but no significant trend using a long-term data in India. Moreover, Vittal et al. [2013] reported disparate trends in extreme rainfall over India in the late 1950 than those observed prior to 1950. They attributed the disparities in extreme rainfall in the pre- and post-1950 to an increased urbanization.

Other than the climate warming, an increased urbanization may also affect extreme precipitation especially in the vicinity of urban areas [Padmanabhamurty and Bahl, 1984; Marshall Shepherd et al., 2002; Kalnay and Cai, 2003; Yang et al., 2014]. Urban expansion has been taking place with a rapid pace in India, which is

strongly associated with the economic growth that the country witnessed during the last few decades [Henderson, 2000]. Moreover, a larger part of global population is expected to be concentrated in urban areas in the coming decades [Cohen, 2006]. Urban areas therefore may be the first responders in adapting to and mitigating climate change [Rosenzweig *et al.*, 2010].

Impervious cover, which is prominent in urban areas, replaces permeable soil that produces more sensible heat and lead to an increased temperature by 2–10°C higher than surrounding non-urban areas [Marshall Shepherd *et al.*, 2002]. Other than the effect of urban heat island, an impervious cover affects runoff generation processes in urban areas leading to flooding. During 1974–2000, a heavy urbanization led to considerably elevated flood risks in the watershed of Upper Thames River [Nirupama and Simonovic, 2007]. Anderson [1968] found that urbanization significantly affected flood flows in Washington, D.C. In July 2005, flash floods in Mumbai, Chennai (October, December), and in Bangalore (October) led to an enormous damage to urban infrastructure and loss of lives [Guhathakurta *et al.*, 2011].

As urban storm water infrastructures are designed based on historic data set assuming stationary conditions, climate change and urbanization may introduce uncertainty in the performance of urban storm water drainage systems in future [Rosenberg *et al.*, 2010; Mishra *et al.*, 2012]. In India, urban areas have been experiencing increased flood events during the recent decades [Gupta and Nair, 2010, 2011]. However, it is somewhat unclear if these increases in urban flooding are caused by increased rainfall events due to climate change or rapid urbanization. Here we intend to address the following scientific questions: (1) *to what extent extreme rainfall events in the major urban areas increased in the last few decades?* (2) *Do rainfall extremes from the satellite data show significant differences for urban and surrounding non-urban areas?* (3) *How reliable are CORDEX-RCMs for evaluating extreme rainfall indices in urban areas of India? and to what extent rainfall extremes in urban areas are projected to change under the projected future climate?*

2. Data and Methodology

We selected 57 urban areas with population more than one million for our study (Figure 1), and more details related to their location are presented in supplemental Table 1. We compared gridded data with the station data for a few urban areas wherever long-term data are available (Supplemental Figure 1). Differences between gridded data and station data are obvious and can be attributed to the gridding process. For the present study, though the station data from urban areas would have been more suitable, we did not use the station data because of gaps and other inconsistencies (changes in the station location and spurious trend). We used gridded data as it is better quality controlled and available for entire India for the long-term period (1901–2010). We obtained the high resolution (0.25 degree) daily rainfall data from the Indian Meteorological Department (IMD) for a period of 1901–2010. Daily rainfall records from 6955 rain gauge stations with varying periods were obtained from the archive of National Data Centre at IMD, Pune for the period of 1901–2010. After applying standard quality checks (geographic location checks, checks for coding and typographic errors) on rainfall data, the simplest form of inverse distance weighted (IDW) interpolation scheme was used for interpolating data to fixed spatial grids of 0.25° × 0.25° resolution [Pai *et al.*, 2014]. Pai *et al.* [2014] reported that the large scale climatological features of rainfall over India derived from the new 0.25° × 0.25 data set were comparable with the existing IMD rainfall data sets at 0.5° × 0.5° and 1° × 1° resolutions [Rajeevan *et al.*, 2008; Rajeevan and Bhate, 2009]. In addition, spatial rainfall distribution like heavy rainfall areas over the orographic regions of the west coast and northeast and low rainfall in the leeward side of the Western Ghats were more realistic and better represented in the new data set due to its higher spatial resolution and station density.

Daily rainfall data from the Tropical Rainfall Measurement Mission [TRMM, Huffman *et al.*, 2007] at 0.25 degree spatial resolution for the period 1998 to 2013 were used to differentiate extreme rainfall indices in urban and surrounding non-urban areas. Urban areas shape files were downloaded from the Natural Earth website (<http://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-urban-area/>), and buffer of 25 km was made in Arc GIS 10.1. Urban areas polygons are derived using 500 m urban extent as described in Schneider *et al.* [2003]. We used a 25 km surrounding non-urban area for the comparison so that the influence of climate, elevation, and other geographical factors can be minimized [Mishra and Lettenmaier, 2011].

To evaluate an effectiveness of regional climate models to simulate daily rainfall in the urban areas, we used historic simulations of daily rainfall data for the period of 1951–2005, which were obtained from the four

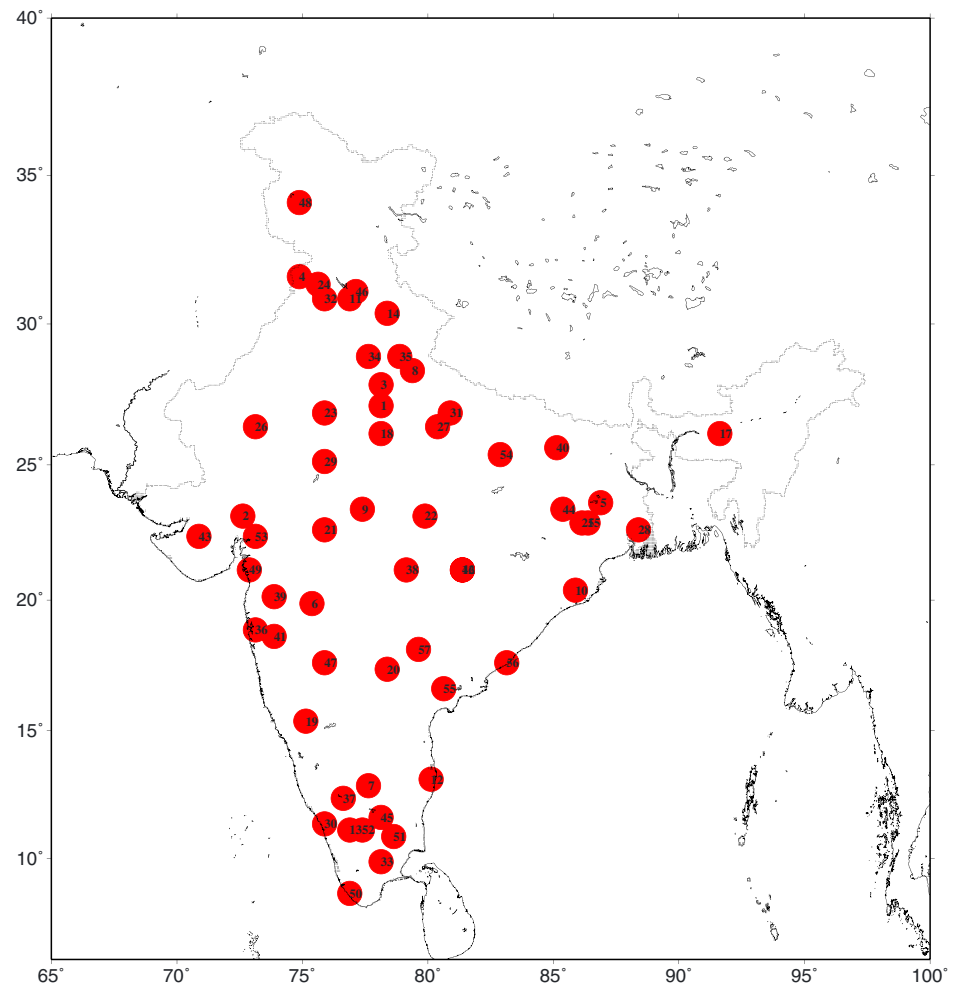


Figure 1. Location of the selected urban areas; further details are provided in supplemental Table 1.

regional climate models (RCMs) that participated in the Coordinated Regional Climate Downscaling Experiment (CORDEX, <http://cccr.tropmet.res.in/cordex/index.jsp>) South Asia: COSMO-CLM, RegCM4-GDCL, RegCM4-LMDZ, and SMHI-RCA4. As data were not available from all the models for the projected future climate, we used data from the three RCMs (COSMO-CLM, RegCM4-LMDZ, and SMHI-RCA4) for the period of 2010–2060. The CORDEX-South Asia data set are available at 0.5 degree spatial and daily temporal resolutions. Though higher spatial and temporal resolutions [Tripathi and Dominguez, 2013] may have been suitable for our analysis, we used data from the CORDEX regional climate model as this is the most advanced dynamically downscaled data set for the Indian Monsoon region. Furthermore, as the presence of significant intermodal variations in a limited ensemble members may produce a large uncertainty [Mishra *et al.*, 2014], more number of regional climate models may provide better estimates for the future projections of extreme rainfall events. We did not apply any downscaling or bias correction to the CORDEX data as we aimed to evaluate dynamically downscaled rainfall for urban rainfall extremes. Since the CORDEX and IMD data sets were at different spatial resolutions, we applied Areal Reduction Factor (ARF) to correct rainfall intensities from 0.5 to 0.25 degree spatial resolutions. We used the method of Leclerc and Schaake [1972] to estimate ARF.

$$ARF = \frac{Z_E}{Z_T} = 1 - e^{-1.1t^{0.25}} + e^{(-1.1t^{0.25} - 0.01A)}$$

where Z_E is areal average effective rainfall and Z_T is total point rainfall, A is area in square kilometer, and t is temporal resolution. This method has been used in many previous studies [Mishra *et al.*, 2012; Tripathi and Dominguez, 2013].

To understand changes in the major urban areas in India, we estimated four rainfall indices for the period of 1901–2010. We considered 1961–1990 as the reference period for our analysis. We estimated the monsoon (June through September) maximum rainfall (maximum daily rainfall for the monsoon season MMR), mean rainfall for the top five events in each year (R-5), frequency (R-FREQ) of extreme rainfall based on 90th percentile of rain days (rainfall > 1 mm) in the reference period (1961–1990), and heavy to non-heavy ratio (H-NH). H-NH was estimated for each year considering rainfall total from extreme rainfall events exceeding 90th percentile as heavy rainfall, while non-heavy rainfall was estimated after subtracting heavy rainfall from annual rainfall total. We selected the 90th percentile as a threshold to obtain a continuous time series of the rainfall indices, which is essential for trend estimation.

To estimate linear trends in the extreme rainfall indices (MMR, RR-5, R-FREQ, and H-NH), the non-parametric Mann-Kendall test was performed considering time series may not follow Normal Distribution [Pal and Al-Tabbaa, 2009]. The Mann-Kendall method was used to estimate linear (monotonic) trends. Statistical significance was estimated at 5% significance level using standardized test static (Z) and *P*-value. More details on the trend analysis can be obtained from Yue and Wang [2002]. First, we estimated percentage anomaly with respect to mean of the reference period (1961–1990) and then the Mann-Kendall test was applied. The effect of spatial and temporal correlations in the data set was considered by using the modified Mann-Kendall method as described in Yue and Wang [2002]. To obtain changes in extreme rainfall indices, we multiplied trend slope with the duration of the selected period. The Mann-Kendall test has been widely used for estimating trends for various hydrologic and climate change impact studies [Pal and Al-Tabbaa, 2009; Mishra et al., 2010; Guhathakurta et al., 2011].

To find nonlinear trends, we used the Ensemble Empirical Mode Decomposition (EEMD) [Wu and Huang, 2009]. The EEMD considers both linear as well as nonlinear trends in the time series. More information on the method and its application can be obtained from Wu and Huang [2009] and Wu et al. [2011]. Wu et al. [2011] demonstrated the effectiveness of the EEMD to identify Secular Trends (ST) and Multi Decadal Variability (MDV). For any period, linear trends are based on ST, and the influence of MDV on the overall trend is not considered. Therefore, empirical modes obtained from raw time series for ST and MDV provide information on overall trends (rather than just linear trends) in time series. This is important for understanding the role of long-term variability on trends in the extreme rainfall indices. We estimated a statistical significance in the changes in mean of the selected rainfall extremes using the two sided Ranksum test at 5% significance level.

In order to estimate rainfall maxima for selected duration (1–3 days) and return periods (100 year), we used Generalized Extreme Value (GEV) distribution based on L-moment approach [Hosking, 1997]. L-moments are less influenced by presence of outliers in time series [Rosenberg et al., 2010; Mishra et al., 2012]. The GEV distribution assumes rainfall intensity to be a Gamma Distribution and has three parameters: location parameter (μ), shape parameter (k), and scale parameter (σ) of the extremes in the database [Katz et al., 2002; Fowler et al., 2010; Mishra et al., 2012].

3. Results and Discussion

3.1. Long-Term Trends in Extreme Rainfall Indices

We evaluated trends in MMR, R-5, R-FREQ, and H-NH for the period of 1901–2010 (Figure 2, supplemental Table 1). Between 1901 and 2010, four out of the total 57 urban areas show significant (*p*-value < 0.05) increasing trends in MMR with a median increase of 24.62% (Figure 2i). All the urban areas (Bhopal, Indore, Hyderabad, and Surat) that show significant increases in MMR during the period of 1901–2010 are located in the west-central India (Figure 2a). On the other hand, a majority of the urban areas with significant (*p*-value < 0.05) declines in MMR are located in the northern India (in the Gangetic Plain region). Median decrease in urban areas with significant declining trends in MMR is 37.9% (Figure 2i). Interestingly, urban areas with significant declines are more than those with significant increases during the period of 1901–2010.

Between the period, only five (Coimbatore, Hyderabad, Surat, Solapur, and Kolkata) urban areas exhibit statistically significant (*p*-value < 0.05) increasing trends in R-5 with a median increase of 25.89% (Figures 2b and 2j). Urban areas showing significant declines in R-5 (median 44.61%) are higher than those with significant increases, and the majority of them are located in the Indo-Gangetic plain and western peninsula. Only four urban areas (Coimbatore, Kolkata, Solapur, and Surat) exhibit significant increases in the frequency of extreme rainfall events (R-FREQ) during the period of 1901–2010 (Figure 2c). Moreover, a majority of urban areas located in the Gangetic Plain region show significant declines in R-FREQ.

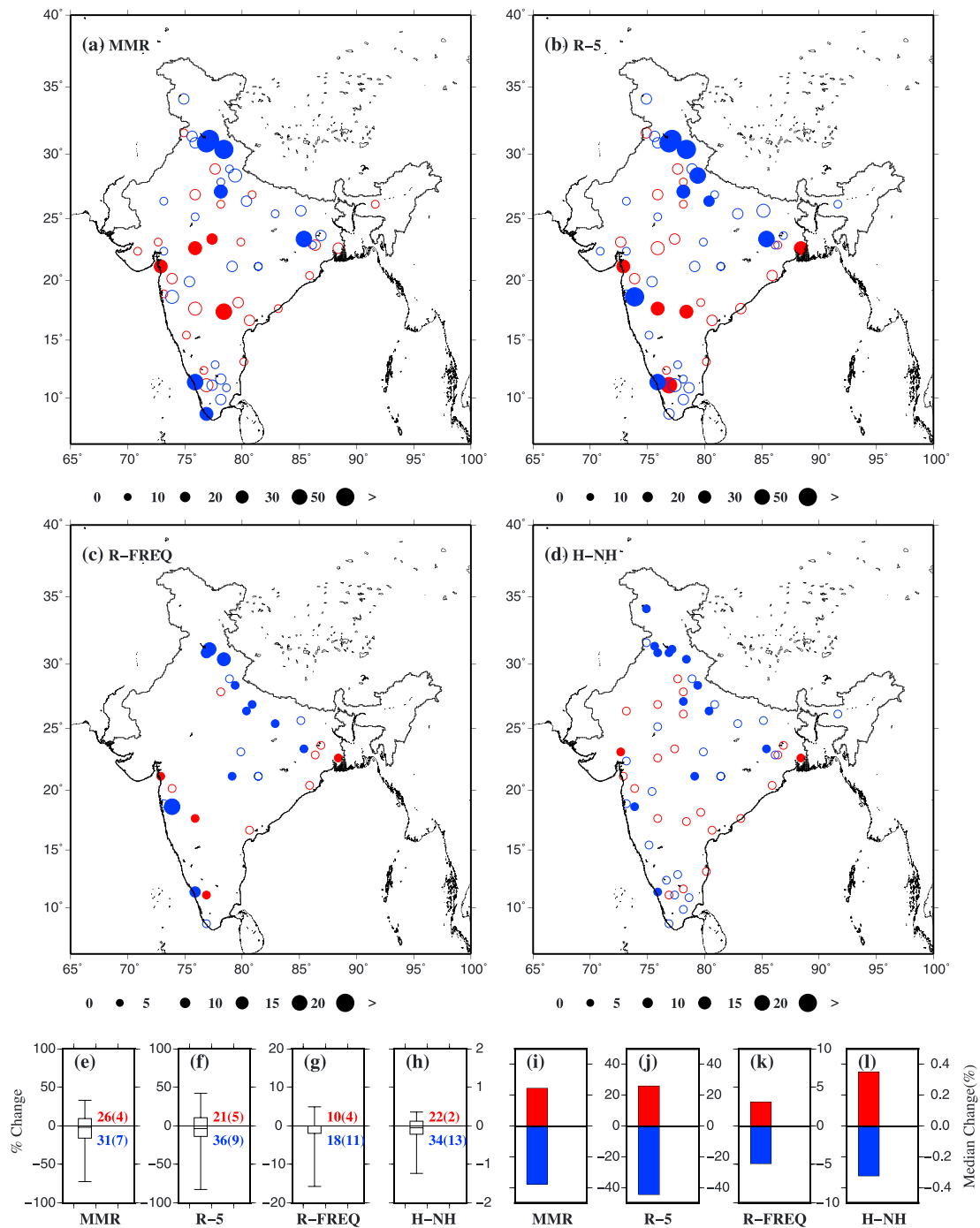


Figure 2. (a) Changes (%) in the Monsoon Maximum Rainfall (MMR), (b) mean rainfall intensity of top five events in a year (R-5), (c) frequency (R-FREQ) of extreme events (90th percentile of rainy days), (d) ratio of heavy to non-heavy rainfall (H-NH) for the period of 1901–2010, (e–h) distribution of % change in MMR, R-5, R-FREQ, and H-NH, respectively, (i–l) median change (in %) in trends in MMR, R-5, R-FREQ, and H-NH, respectively, for all urban areas. Boxes represent median, lower, and upper quartiles; whiskers extend from minimum to maximum values. Numbers right of boxes indicate urban areas with positive (red) and negative (blue) changes. Numbers in parentheses represent urban areas with statistically significant changes at 5% significance level (two-sided test). Red circle shows increasing trend; blue circle shows decreasing trend. Unfilled circle shows insignificant trend; filled circle shows significant trend at 5% significance level.

Contribution of heavy rainfall to total annual rainfall (H-NH) increased at only two urban areas (Kolkata and Ahmadabad) during the period of 1901–2010 (Figure 2d). On the other hand, many urban areas located in the Gangetic Plain and Southern Peninsula exhibit significant declines in H-NH (Figure 2d, supplemental Table 1). While we notice that different extreme rainfall indices show disparate changes in urban areas during

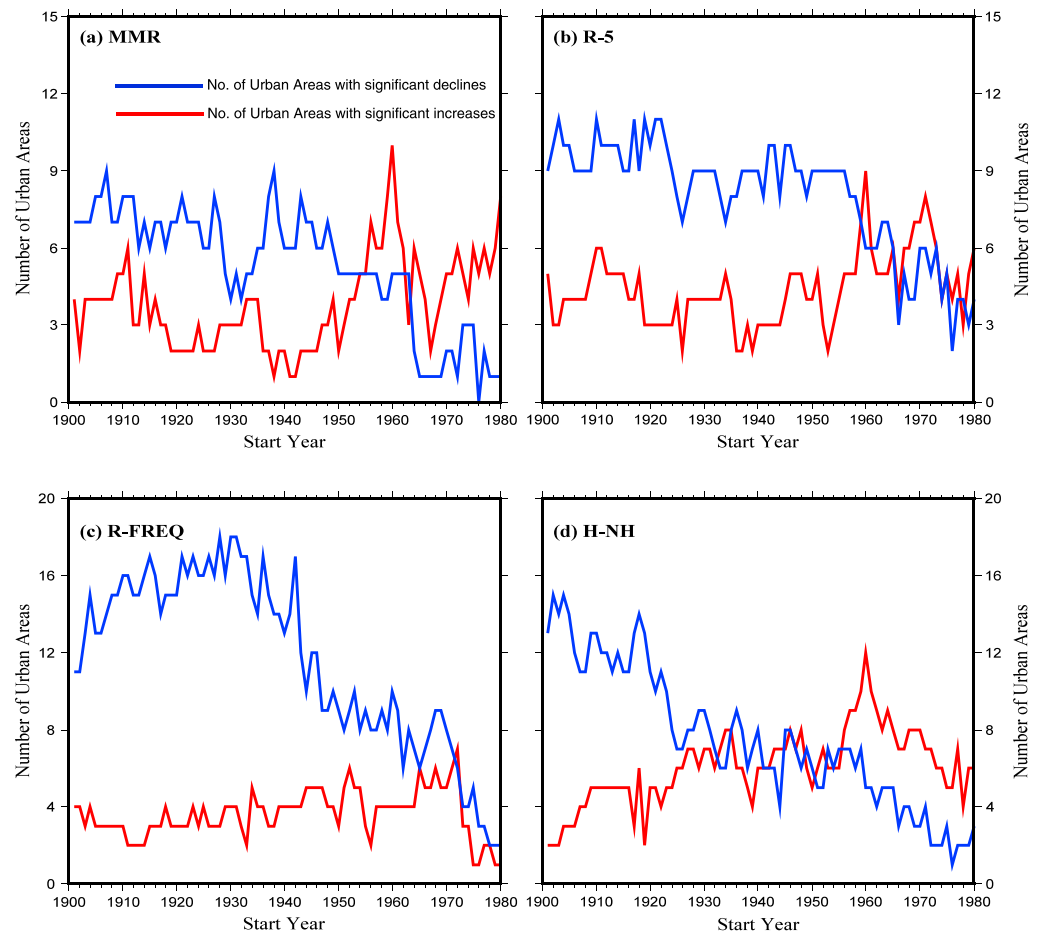


Figure 3. Number of urban areas with significant increasing (red color) and decreasing trends (blue color) for (a) MMR, (b) R-5, (c) R-FREQ, and (d) H-NH. Trends were estimated for all periods with start years varying from 1901 to 1980 and end year 2010.

the period of 1901–2010, urban areas located in the Gangetic Plain and Southern Peninsula experienced significant declines in the majority of the extreme rainfall indices. These results further highlight a need to consider multiple indices in order to assess trends/changes in extreme rainfall events over the major urban areas. Our results do not show significant increases in the extreme rainfall indices in the majority of urban areas in India during the period of 1901–2010. Goswami *et al.* [2006] reported significant rising trends in frequency and magnitude of extreme rain events over the central India using an averaged time series for the entire region for the period of 1951–2000. Disagreement with the findings of Goswami *et al.* [2006] can be attributed to differences associated with period and approach (averaged over an area vs. point estimates) of analysis. However, our results are consistent with the findings of Ghosh *et al.* [2009], who reported no significant increase in extreme rainfall in India using the 1 degree gridded data set. Moreover, we find a significant (p -value < 0.05) decline in the frequency of extreme events (11 cities) in India using long-term data, which is in agreement with the previous studies [Dash *et al.*, 2009; Ghosh *et al.*, 2009; Krishnamurthy *et al.*, 2009].

3.2. Time-varying Trends in Extreme Rainfall

As trends/changes may vary in the different time periods, we estimated the number of urban areas showing significant increases and declines in the extreme rainfall indices for periods (Figure 3) with different starting years and with the same ending year of 2010. We observe a decline in number of urban areas with significant (p -value < 0.05) decreasing trend in all the indices for the recent decades (Figures 3a–3d). On the other hand, we find an increase in number of urban areas with significant uptrends in all the indices up to a certain period (1960–2010). Urban areas showing a significant increasing trend in MMR are the largest (10, i.e., 17.5% of urban areas) for the period of 1960–2010. The number of urban areas with a significant increasing trend in R-5 is the largest (9 i.e. 16% of urban areas) for the period 1960–2010. The largest number of urban areas showing

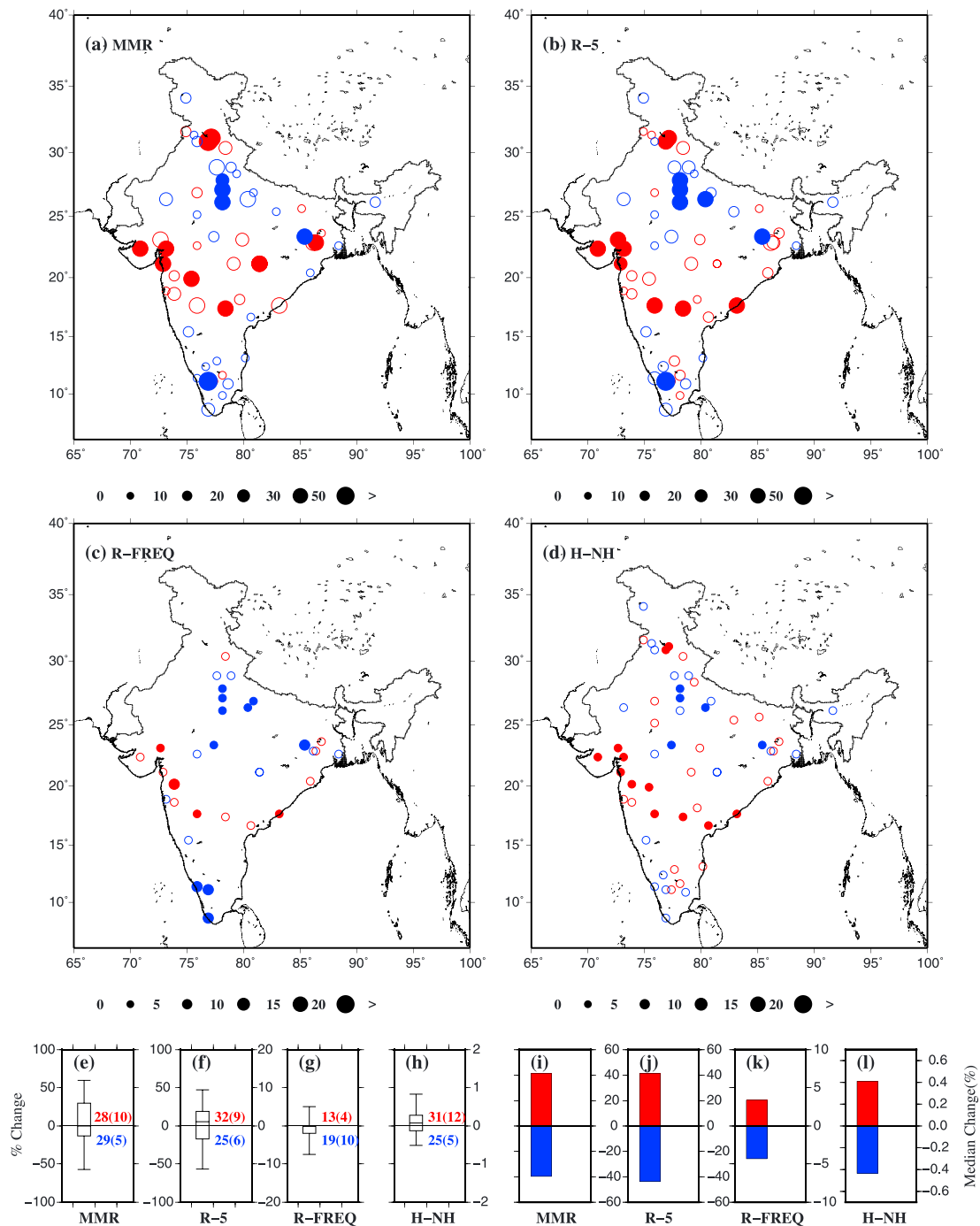


Figure 4. Same as Figure 2 but for the period 1960–2010.

significant increasing trend are 7 (12.28%) and 13 (22.8% of total urban areas) for R-FREQ and H-NH, respectively. Therefore, when we analyze trend over different time periods, there are only a few urban areas (23% or less) that exhibit significant increasing trend, indicating possibly an impact of climate variability on extreme rainfall events over the major urban areas in India.

Since the periods 1960–2010 and 1971–2010 show a relatively more number of urban areas with significant increases in the extreme rainfall indices, we further analyzed variability of trends in urban areas for these periods (Figures 4 and 5). Statistically significant (p -value < 0.05) increases in MMR, R-5, R-FREQ, and H-NH are observed at 10 (median 41.42%), 9 (median 41.41%), 4 (median 3.37%), and 12 (median 0.41%) urban areas,

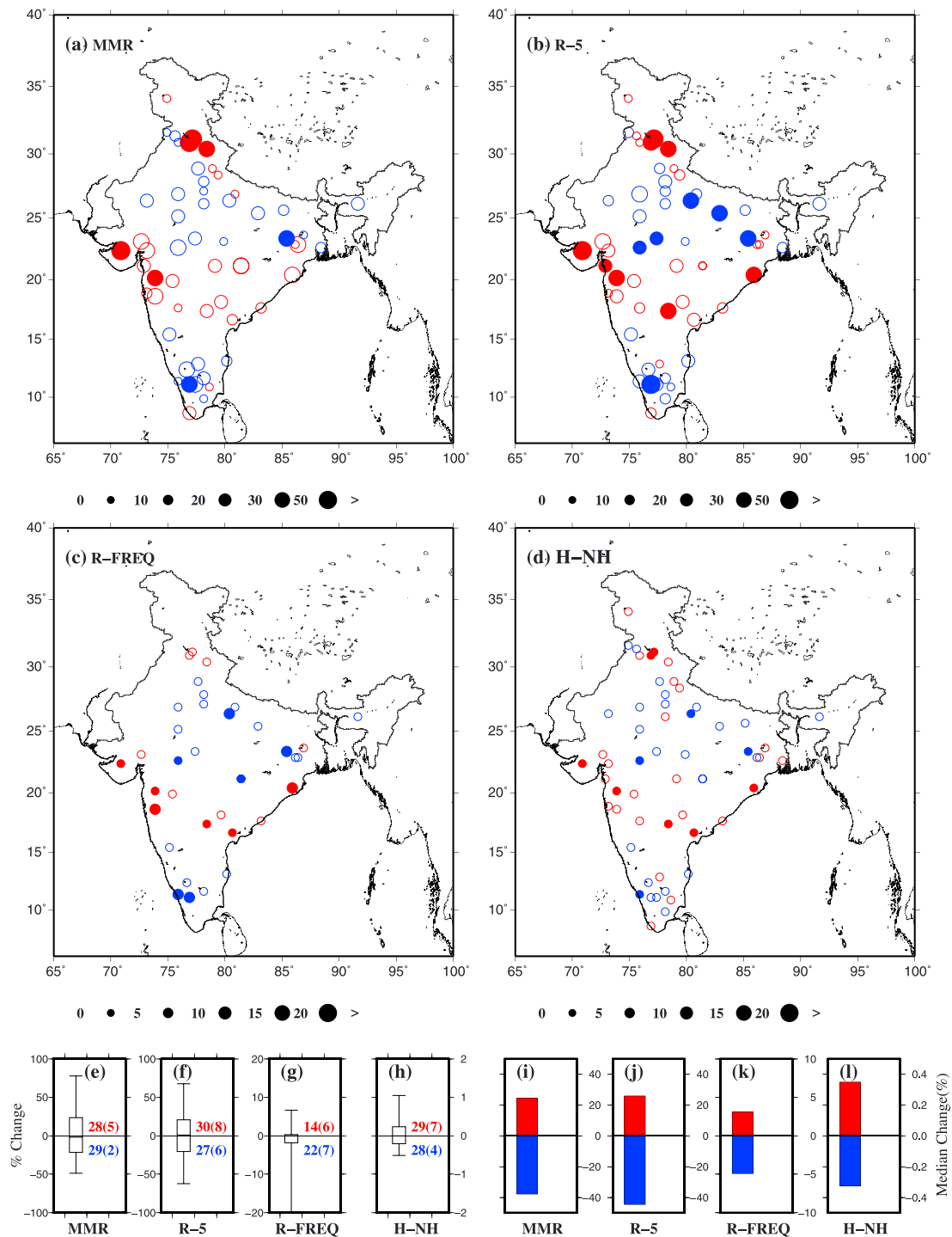


Figure 5. Same as Figure 4 but for the 1970–2010 period.

respectively, during the period of 1960–2010. In the peninsular India, only Coimbatore shows a significant change in MMR and R-5. On the other hand, a few urban areas (Coimbatore, Thiruvananthapuram, and Kozhikode) witnessed a significant decline in R-FREQ. Similarly, for the period of 1971–2010, urban areas with significant increases (declines) in the extreme rainfall indices are located in the west-central (Gangetic Plain) region (Figure 5). We observe statistically significant increases in MMR, R-5, R-FREQ, and H-NH at 5 (median 55.57%), 8 (median 44.8%), 6 (median 4.87%), and 7 (median 0.69%) urban areas, respectively. Urban areas with

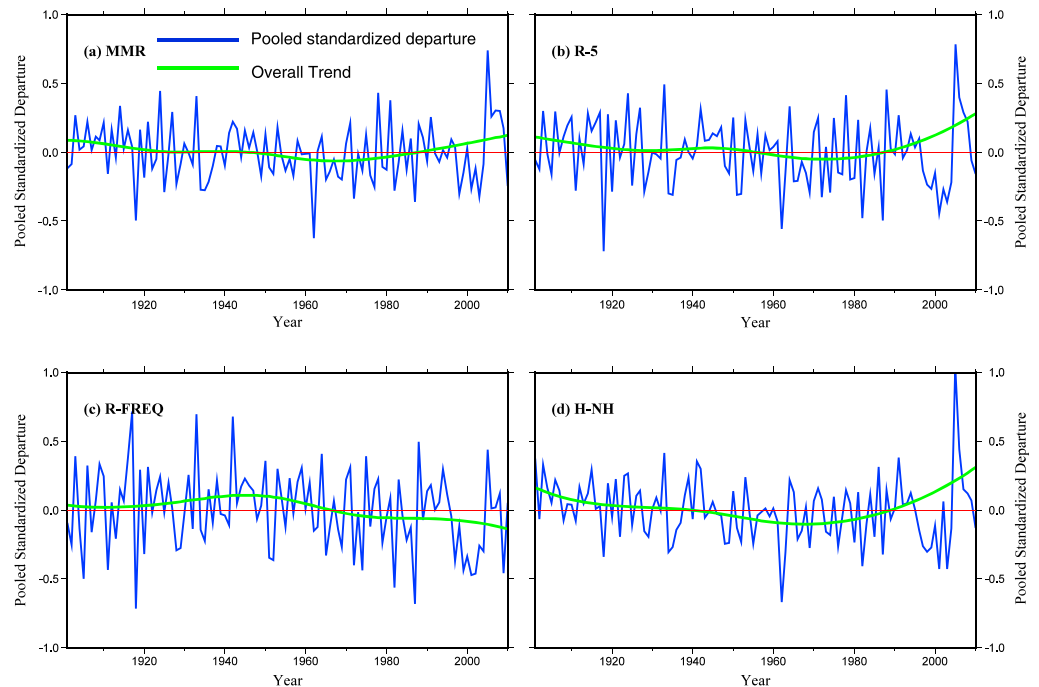


Figure 6. Pooled (for all 57 urban areas) standardized departure of (a) MMR, (b) R-5, (c) R-FREQ, and (d) H-NH for the period of 1901–2010. The green line shows overall trend (ST: secular trend + MDV: Multi Decadal Variability) estimated using the Ensemble Empirical Model Decomposition (EEMD).

significant positive trends in the extreme rainfall indices increased during the recent decades (1960–2010 and 1971–2010) in comparison to the entire period (1901–2010). Moreover, the number of urban areas with significant negative trends declined during the recent decades. These variations can be attributed to different periods selected for the trend analysis as well as associated large-scale climatic variability. For instance, urban areas that show significant trends for a longer duration (110 years) do not exhibit the similar trends for shorter durations (50 and 40 years). Kolkata showed significant increases in trends in the all indices (except MMR) for the period 1901–2010; however, it does not show any significant trend for the periods of 1960–2010 and 1971–2010. These results highlight the time-varying nature of trends in the extreme rainfall indices.

We estimated standardized departure (Z score) in the extreme rainfall indices for each urban area for the period of 1901–2010. This was particularly done to avoid influence of urban areas with high values of rainfall extremes on the average time series. Pooled standardized departure was estimated by taking mean of standardized departures from individual urban areas (Figure 6). Pooled standardized departure of all the extreme rainfall indices reveals a large scale (multi-decadal) variability, which is also indicated by the wavelet analysis (supplemental Figure 2). For instance, between 1901 and 1955, the extreme rainfall indices except R-FREQ showed a minimal trend. On the other hand, the extreme rainfall indices showed a decline for the period of 1955–2000. On the basis of behavior of trends in the extreme rainfall indices (Figure 6), we divided the entire time series into two equal periods, i.e., pre-1955 and post-1955 to consider a potential role of climatic change on rainfall extremes. During the recent decades, there has been an increase in the extreme rainfall indices as shown by pooled standardized departure (Figure 6). Overall trends (ST + MDV) estimated using EEMD also demonstrate a presence of multi-decadal variability rather than a monotonic trend in the extreme rainfall indices over the major urban areas in India.

We estimated trends in the extreme rainfall indices using periods with different starting and ending year (rather than fixing the end year as done earlier) to identify time spans that show the largest number of urban areas with significant increases and declines in the extreme rainfall indices (Figure 7). Urban areas showing significant (p -value < 0.05) increases in MMR are found to be maximum for the periods with starting year ranging from 1955 to 1980 and ending year ranging from 2007 to 2010 (Figure 7a). We observe that the periods with ending year before 2006 have a lesser number of urban areas with significant increases in MMR, which indicates that these positive trends are mainly due to increases in extreme rainfall that occurred in the

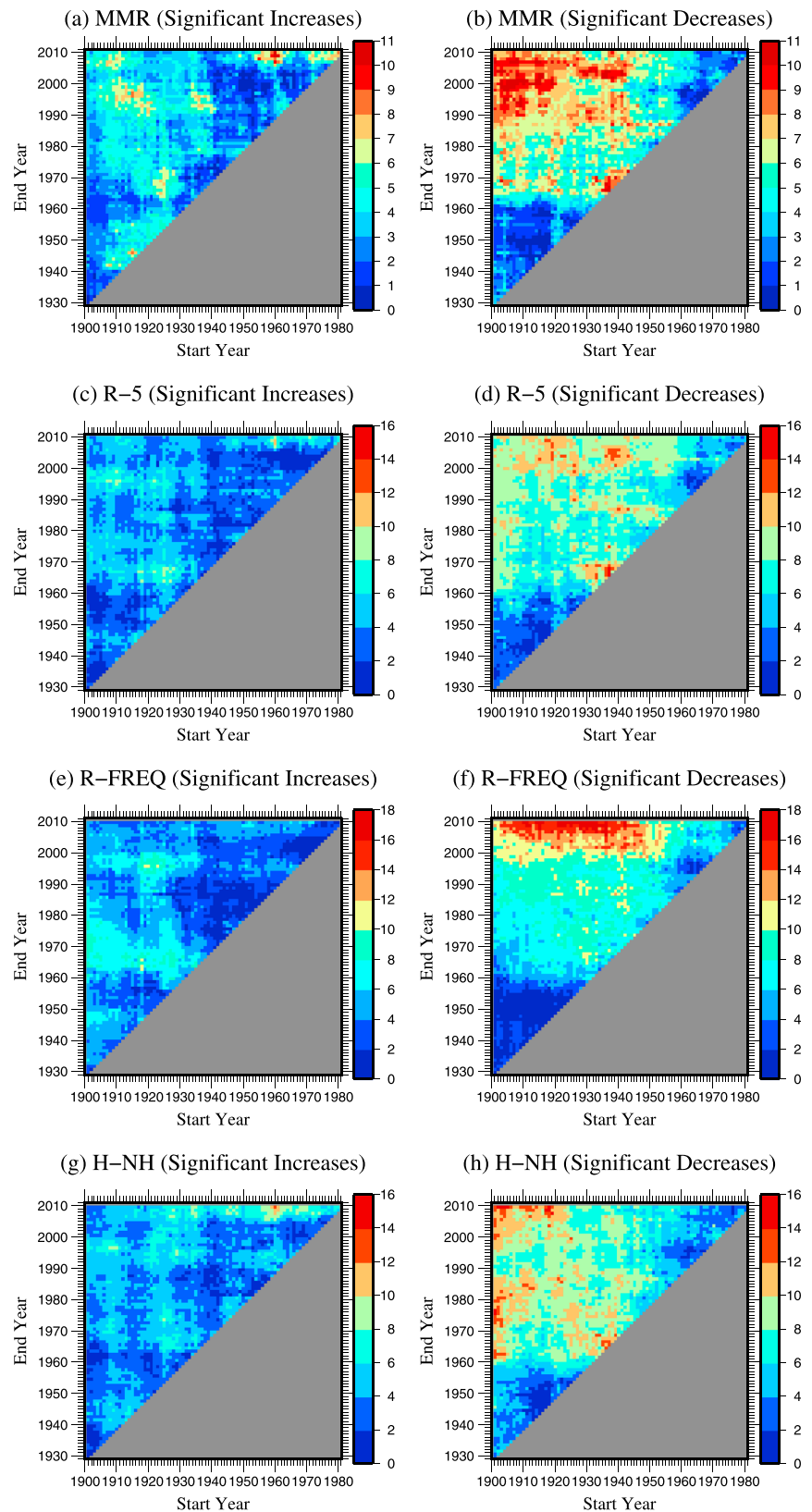


Figure 7. (a, c, e, and g) Number of urban areas with significant increasing trend in MMR, R-5, R-FREQ, and H-NH, respectively. (b, d, f, and h) same as Figures 7a, 7c, 7e, and 7g but for a significant decreasing trend. For periods with different start year (1901–1980) and end year (1930–2010).

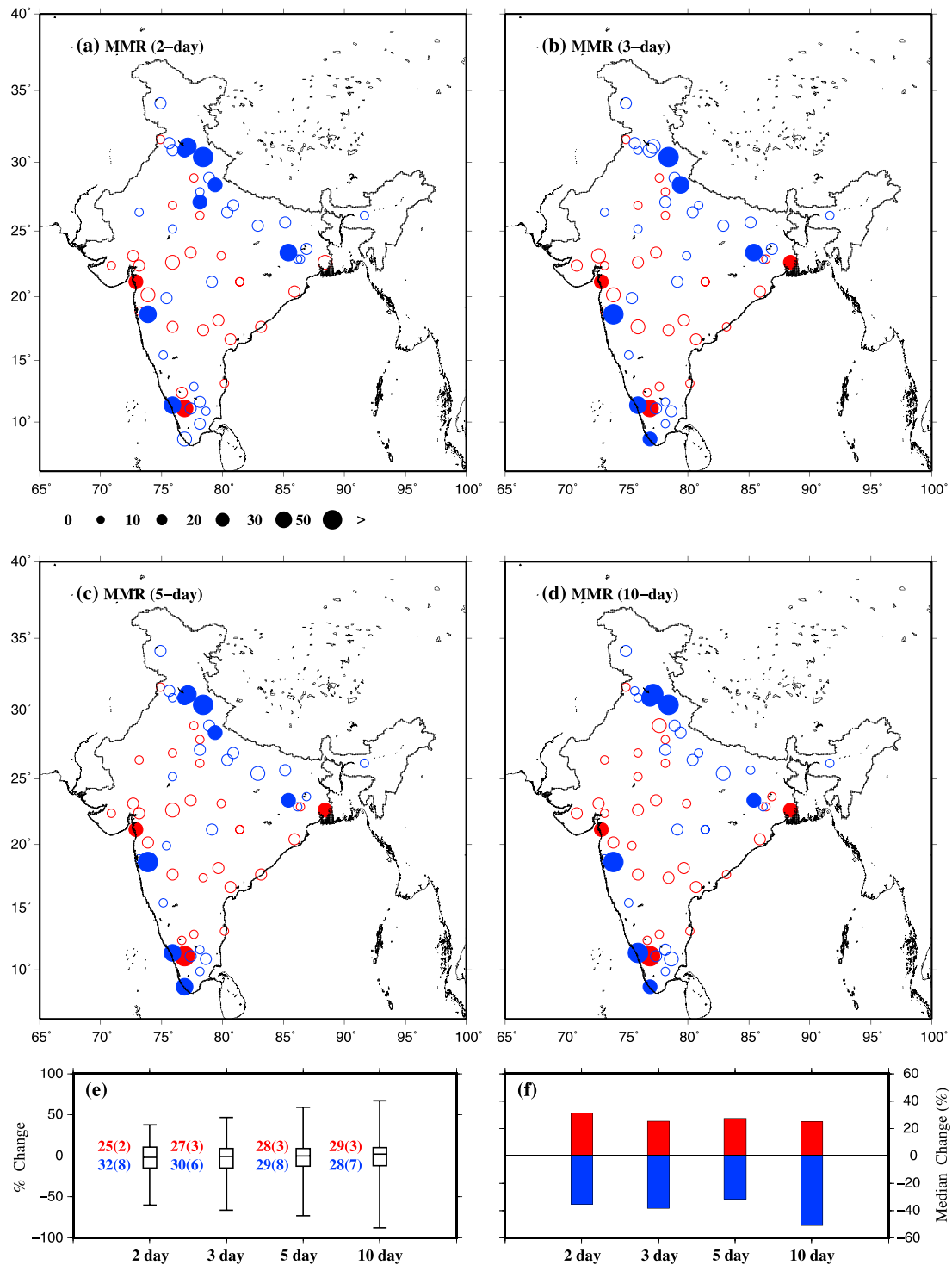


Figure 8. Trends (%) in (a) 2 day MMR, (b) 3 day MMR, (c) 5 day MMR, and (d) 10 day MMR, (e) distribution of % changes for 2, 3, 5, and 10 day MMR for urban areas, and (f) median trends (%) for all urban areas for the period of 1901–2010. Boxes represent median, lower, and upper quartiles; whiskers extend from minimum to maximum values. Numbers left of boxes indicate urban areas with positive (red) and negative (blue) changes. Numbers in parentheses represent urban areas with statistically significant changes at 5% significance level (two-sided test) Red circle shows increasing trend; blue circle shows decreasing trend. Unfilled circle shows insignificant trend; filled circle shows significant trend at 5% significance level.

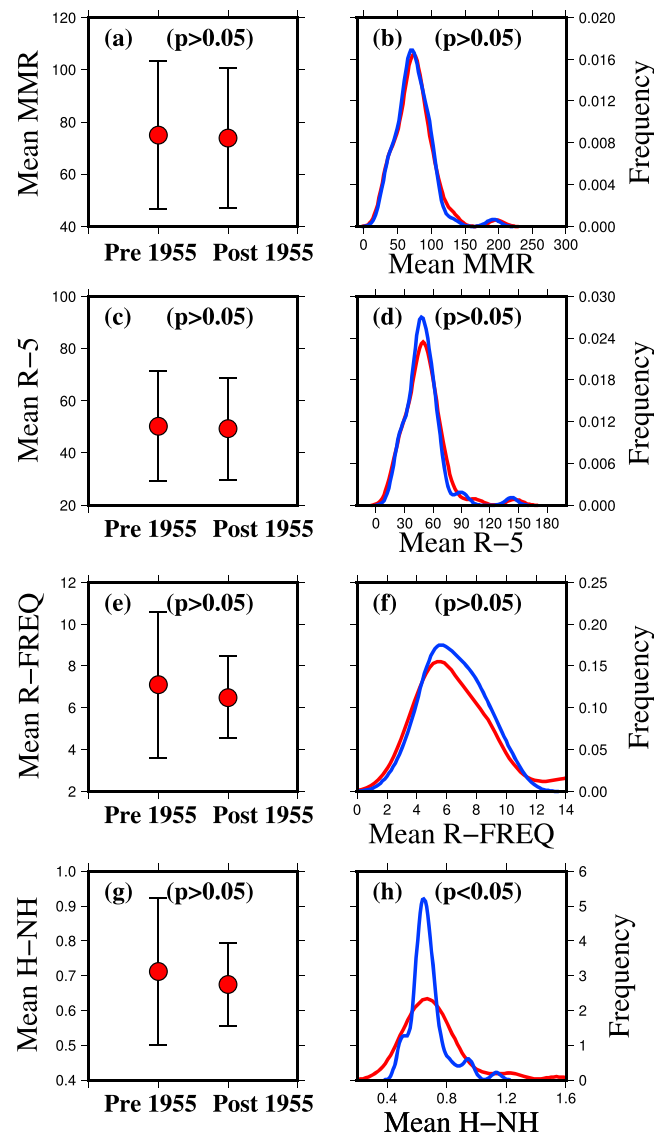


Figure 9. (a, c, e, and g) Pooled (for all urban areas) mean MMR (mm), R-5 (in mm), R-FREQ, and H-NH, respectively, for the pre- and post-1955 periods, (b, d, f, and h) pooled distributions for mean MMR, R-5, R-FREQ, and H-NH, respectively, for the pre- (red) and post- (blue) 1955 periods. Error bars show range of one standard deviation from the mean. Statistical significance was estimated using the Ranksum and KS tests for mean and distributions of the extreme rainfall indices.

respectively (Figure 8). For the same period, significant (p -value < 0.05) increases in trends in 1 day MMR are observed at four urban areas with a median increase of 24.62% (Figures 2a, 2e, and 2f). For 2 and 3 day MMR, significant declining trends (median 35.34% and 38.47%, respectively) are observed at 8 (Agra, Bareilly, Dehradun, Kozhikode, Pune, Shimla, Chandigarh, and Ranchi) and 6 urban areas (Bareilly, Dehradun, Kozhikode, Pune, Ranchi, and Thiruvananthapuram), respectively. On the other hand, significant declines in 5 and 10 day MMR (median 31.5% and 50.8% respectively) are observed at 8 and 7 urban areas, respectively, and many of them are located in the Indo-Gangetic plains and western coast. Moreover, the majority of urban areas do not show significant trends during the period of 1901–2010. Results for multi-day durations for the periods of 1960–2010 and 1971–2010 are shown in supplemental Figures 3 and 4, which show the similar findings. The number of urban areas showing significant trends is somewhat similar for the three periods, which indicates that there is no substantial impact of climate change and/or urbanization on trends in the extreme rainfall indices.

last few years. Decreases in number of urban areas with significant declines in MMR are observed in periods with starting year 1940s onwards (Figure 7b). For R-5, the maximum number of urban areas with significant increases is 11 (Figure 7c). Similarly, 18 out of the 57 urban areas show significant declines in R-5 (Figure 7d). For R-FREQ, a few urban areas (maximum 11) show significant increases for the different periods (Figure 7e). Therefore, time-varying trends for the extreme rainfall indices show that only a few out of the 57 urban areas experienced significant increases in the extreme rainfall indices for different periods. Moreover, our results do not show any significant change in the extreme rainfall indices over the major urban areas in India in the pre- and post-1955 periods (related to climate change) or pre- (1956–1983) and post-1983 periods (related to urban expansion). This highlights that climatic changes (after 1955) and urbanization (after 1983s) might not have a significant impact on rainfall extremes over the major urban areas in India.

3.3. Trends in the Monsoon Maximum Rainfall of Multi-Day Durations

Trends in the extreme rainfall indices may differ with rainfall durations. We therefore evaluated changes in MMR for 2, 3, 5, and 10 day durations for the period of 1901–2010 (Figure 8). We observe significant increases in 2, 3, 5, and 10-day MMR at 2 (median 31.47%, Surat and Coimbatore), 3 (median 25.43%, Kolkata, Surat, and Coimbatore), 3 (median 27.27%, Coimbatore, Kolkata, and Surat), and 3 (median 25.05%) urban areas (Coimbatore, Kolkata, and Surat),

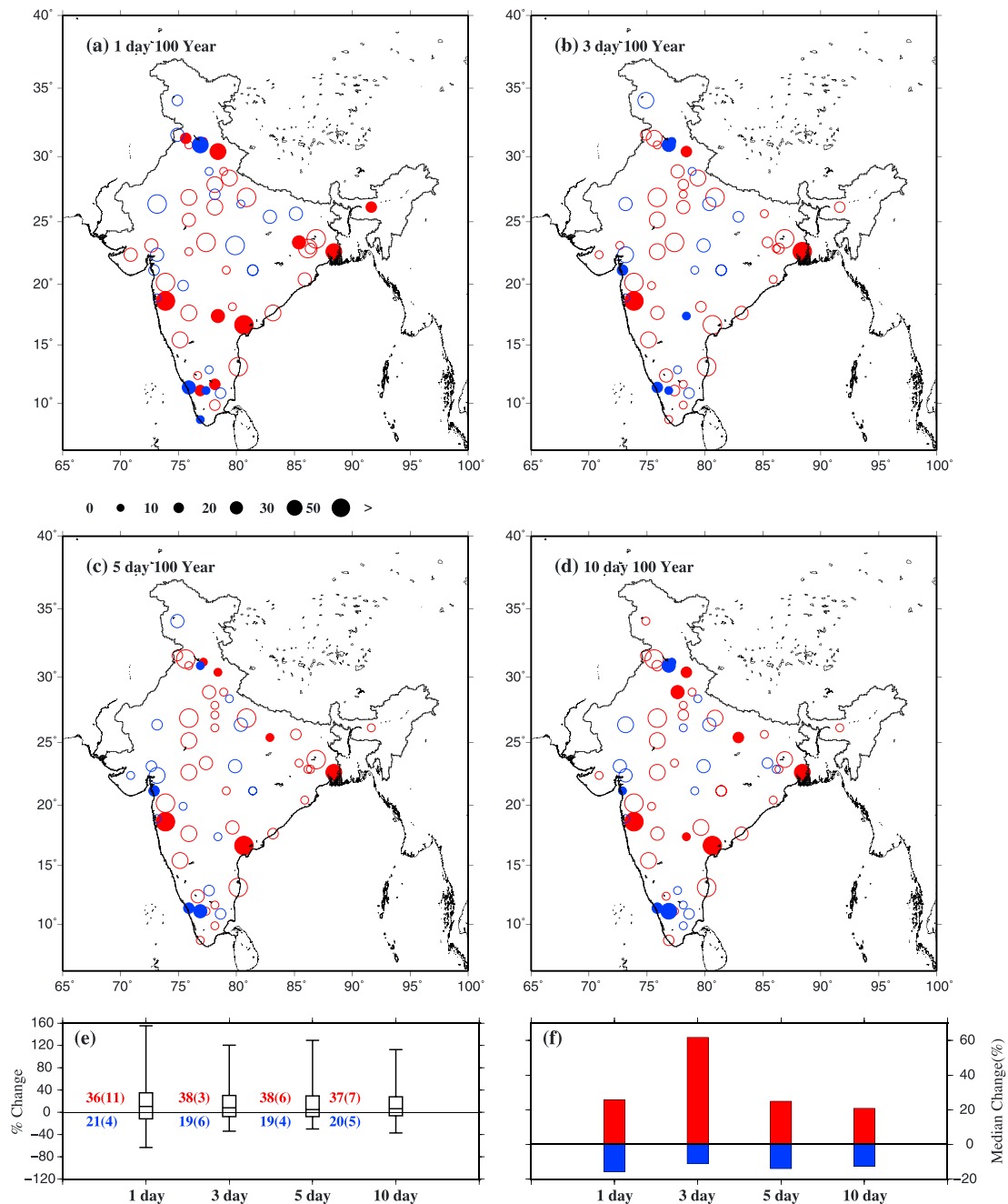


Figure 10. (a–d) Changes (%) in 1–10 day 100 year rainfall maxima for the pre- (1901–1955) and post- (1956–2010) 1955 periods, (e) distribution of % changes for 1, 3, 5, and 10 day 100 year MMR for all the urban areas, and (f) median trends (%) for all urban areas for the pre- and post-1955. Boxes represent median, lower, and upper quartiles; whiskers extend from minimum to maximum values. Numbers left of boxes indicate urban areas with positive (red) and negative (blue) changes. Numbers in parentheses represent urban areas with statistically significant changes at 5% significance level (two-sided test) Red circle shows increasing trend; blue circle shows decreasing trend. Unfilled circle shows insignificant trend; filled circle shows significant trend at 5% significance level.

3.4. Role of Climate Change on Extreme Rainfall Events

For considering the role of climatic change on rainfall extremes in the urban areas, we divided the entire time series into two periods: 1901–1955 and 1956–2010, assuming that in the pre-1955 period the role of climate change was minimal (as seen in Figure 6). We calculated pooled mean and distributions (for all urban areas) for all the four indices and compared them for the pre- and post-1955 periods (Figure 9). Mean and distribution of pooled MMR did not change significantly (p -value > 0.05) from the pre- to post-1955 periods (Figures 9a and 9b).

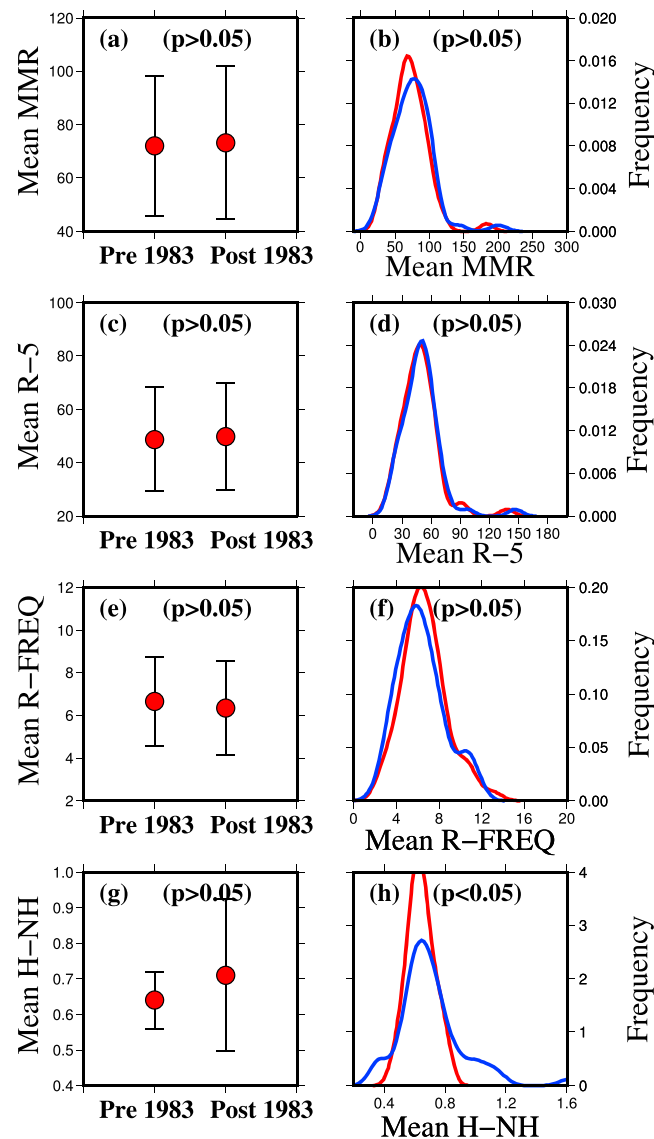


Figure 11. (a, c, e, and g) Pooled (for all urban areas) mean MMR (mm), R-5 (mm), R-FREQ, and H-NH, respectively, for the pre- and post-1983 periods, and (b, d, f, and h) pooled distributions for mean MMR, R-5, R-FREQ, and H-NH, respectively, for the pre- (red) and post- (blue) 1983 periods. Error bars show range of one standard deviation from the mean. Statistical significance was tested using the Ranksum and KS tests for mean and distributions of the extreme rainfall indices.

Similarly, we do not observe any significant change in pooled mean for R-5, H-NH, and R-FREQ for the two periods (Figures 9c–9f). However, it can be noticed that distribution of H-NH has changed significantly for the two periods (Figure 9h) indicating increased variability in the index during the recent decades. To study role of climate change on the performance of the storm water drainage systems, we estimated design storms for 1, 3, 5, and 10 days durations at 100 year return periods for the two periods: 1901–1955 and 1956–2010 (Figure 10). We estimated changes in rainfall maxima at 100 year return interval at each of the selected urban areas for the pre- and post-1955. For 1 day 100 year MMR, 11 urban areas (Coimbatore, Dehradun, Guwahati, Hyderabad, Jalandhar, Kolkata, Pune, Ranchi, Salem, Shimla, and Vijayawada) show significant increases (median 25.74%), while four urban areas (Chandigarh, Kozhikode, Thiruvananthapuram, and Tiruppur) exhibit significant declines (median 15.66%) in the post-1955 period (Figures 10a, 10e, and 10f). For 3 day 100 year MMR, three urban areas (Dehradun, Kolkata, and Pune) show significant increases (median 61.87%), while six (Chandigarh, Coimbatore, Hyderabad, Kozhikode, Surat, and Shimla) urban areas show significant decreases (median 11.2%) in the design storm magnitudes (Figures 10b, 10e, and 10f). For 10 day 100 year, seven urban areas (Dehradun, Hyderabad, Kolkata, Meerut, Pune, Varanasi, and Vijayawada) show significant increases (median 20.9%), while five urban areas (Chandigarh, Coimbatore, Kozhikode, Shimla, and Surat) witnessed significant declines (Figures 10d, 10e, and 10f). These results indicate that at the majority of urban areas, rainfall maxima at 100 year return period did not change significantly during the post-1955 period. Moreover, the number of urban areas with significant declines is larger than those with significant increases. Our results show that increased flooding events in urban areas may not be related to climate change rather these may be associated to the sizing of stormwater drainage systems. For instance, rapid urban expansion warrants modification in storm water infrastructure and in the absence of an improved drainage infrastructure, urban areas are likely to face flooding events regardless of changes in rainfall extremes.

3.5. Role of Urbanization on Extreme Rainfall Events

To evaluate a potential role of urbanization on rainfall extremes in the selected urban areas, we compared the pooled mean and distribution of the extreme rainfall indices for the two periods: 1956–1983 and 1984–2010 (Figure 11). Here, we assume that a rapid urbanization in the post-1983 period may influence trends in the

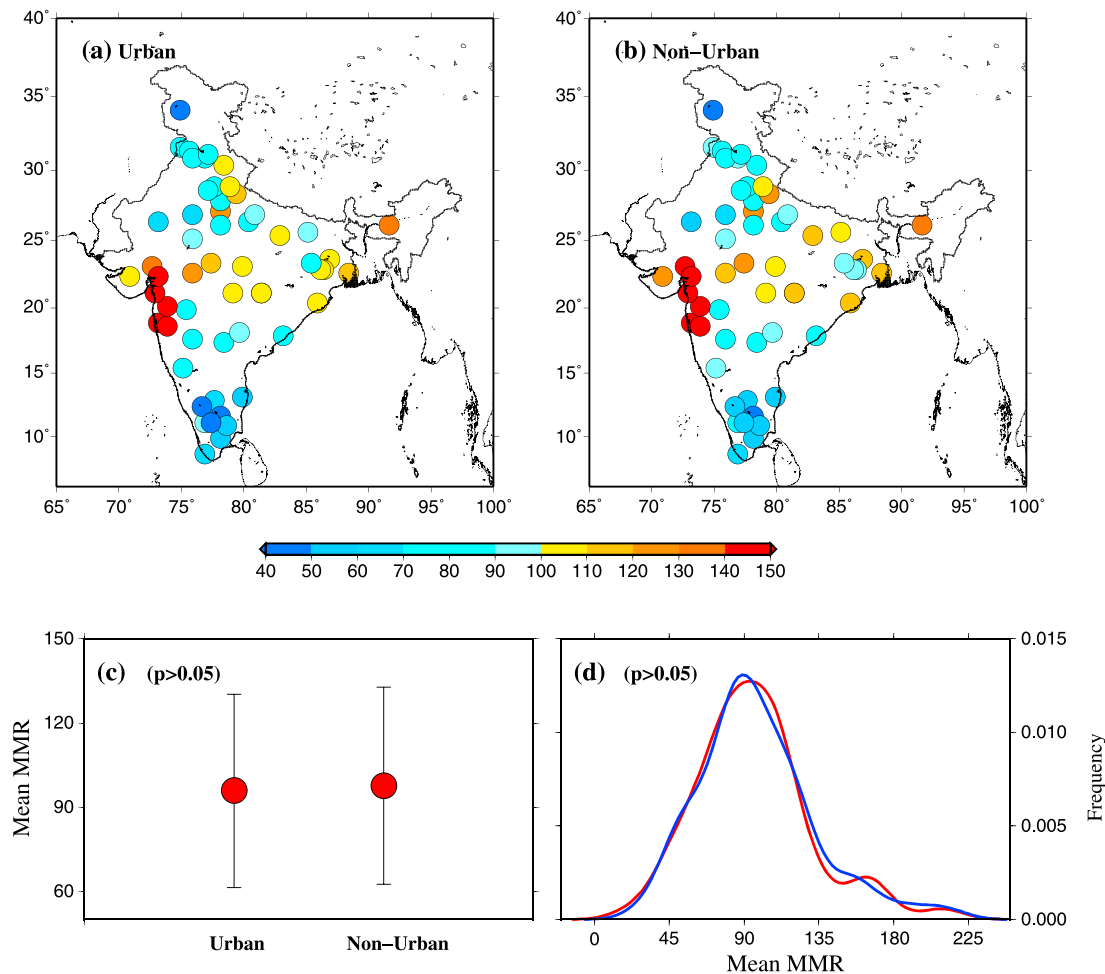


Figure 12. (a–b) MMR (mm) for all urban and surrounding non-urban areas, respectively, estimated using the TRMM data, (c) pooled mean MMR (in mm) for urban and surrounding non-urban areas, and (d) pooled distribution of MMR for urban (red) and non-urban areas (blue) for the period 1998–2013. Error bars show range of one standard deviation from the mean. Statistical significance was estimated using the Ranksum and KS tests for mean and distributions of the extreme rainfall indices.

extreme rainfall indices and differences in magnitude of pooled mean and distribution of the selected rainfall extremes between the two periods will reveal the possible effect of urbanization on rainfall extremes. However, we do not observe any significant changes ($p > 0.05$) in pooled mean and distribution of the extreme rainfall indices for the pre- and post-1983 periods. We notice a relatively small change in the magnitude and distribution of pooled mean of the extreme rainfall indices, which reveals a weaker role of urbanization and/or climate change on rainfall extremes in the major urban areas in India.

In order to differentiate rainfall in urban and surrounding non-urban areas, we calculated MMR for urban areas and surrounding (25 km) non-urban area using daily TRMM data at 0.25 degree resolution because TRMM can easily detect UHI-rainfall effects [Marshall Shepherd et al., 2002]. We observe that there is a minimal difference in MMR for urban and surrounding non-urban areas (Figures 12a and 12b). When we estimate pooled mean MMR and their distribution of all the urban and surrounding non-urban areas, we find no significant difference (Figures 12c and 12d). For instance, mean MMR for all the urban areas is 95.82 mm, while for all the non-urban areas it increases to 97.6 mm. We have also calculated mean MMR for individual urban and surrounding non-urban areas (supplemental Figure 5), which also reveals similar non-significant differences between urban and non-urban areas. The other important feature to note here is related to spatial variability in changes in rainfall extremes over the major urban areas. For instance, a majority of the selected urban areas witnessed substantial increases in urban development; however, urban areas with significant increases in extreme rainfall are located in the west-central India indicating a possible role of the large-scale climate variability on changes in the extreme rainfall indices. Kishtawal et al. [2010] reported significant increasing trend in frequency of

extreme events over urban areas in India and related their findings as a result of urban heat island [Marshall Shepherd *et al.*, 2002; Menon *et al.*, 2010]. Our results, however, show that urban areas in one of the most populated region in the world experienced declining trends associated with extreme rainfall events. The disparate nature of trends in the Gangatic Plain region could be associated with the changes in rainfall characteristics due to atmospheric aerosols as shown in Bollasina *et al.* [2011].

3.6. Rainfall Maxima in Regional Climate Models

To evaluate if current generation of regional climate models can simulate the extreme rainfall indices over urban areas, which is vital for urban storm water designs under the projected future climate change, we used four regional climatic models that participated in the CORDEX-South Asia program: COSMO-CLM, RegCM4-LMDZ, RegCM4-GFDL, and SMHI-RCA4. We evaluated the regional climate models using percentage bias in MMR against the observed data from IMD for the period of 1951–2005. First, percentage bias [(MMR from model – MMR from IMD) / MMR from IMD] was estimated for individual regional climate models then ensemble mean percentage bias was estimated by taking average of bias from the models. For 1 day MMR, COSMO-CLM overestimates MMR for the majority of urban areas (bias up to 472.09% Figure 13a). A few urban areas exhibit a negative bias in MMR (up to –55.107%), while seven urban areas show bias within $\pm 10\%$ that is considered suitable for hydrologic designs. RegCM4-LMDZ, RegCM4-GFDL, and ensemble mean of the selected regional climate models overestimate MMR at only a few urban areas located in northern and southern India (Figures 13b–13d), while the rest of the urban areas show negative bias in MMR. Moreover, SMHI-RCA4 largely underestimates MMR at majority of urban areas across India (Figure 14d). Bias for all the selected urban areas is presented in supplemental Table 2.

We estimated bias in 1, 2, and 3 day 100 year MMR from the four RCMs and their ensemble mean against the observations from IMD. For 1, 2, and 3 day 100 year rainfall maxima, COSMO-CLM overestimates MMR for the most urban areas (Figures 13f, 13k, and 13p). The number of urban areas that shows $\pm 10\%$ bias is 10, 13, and 10, respectively, for 1, 2, and 3 day MMR at 100 year return interval. RegCM4-LMDZ underestimates 1–3 day rainfall maxima at 100 year return period for the most urban areas (Figures 13g, 13l, and 13q). We notice a few urban areas with positive bias in 1–3 day rainfall maxima at 100 year return period located in the central and southern regions of India in RegCM4-GFDL (Figures 13h, 13m, and 13r), while at rest of the urban areas rainfall maxima is largely underestimated. SMHI-RCA4 shows overestimations in rainfall maxima at urban areas located in the Indian peninsula and Srinagar (Figures 13i, 13n, and 13s), and urban areas with bias within $\pm 10\%$ in 1, 2, and 3 day 100 year MMR are observed to be 13, 10, and 12, respectively. RCMs show bias in simulated rainfall maxima at the selected urban areas that could be associated to both model parameterizations and resolution [Gutowski *et al.*, 2010; Wehner *et al.*, 2009]. Simulating extreme rainfall events with reasonable intensity and frequency remains a challenge [Toreti *et al.*, 2010], therefore, models need to be improved for parameterization as well as for spatial and temporal resolutions in order to simulate rainfall extremes over urban areas [Mishra *et al.*, 2012; Tripathi and Dominguez, 2013].

3.7. Projected Changes in Rainfall Maxima

To understand changes in storm water designs under the projected climate, we used rainfall data from the three RCMs (COSMO-CLM, RegCM4-LMDZ, and SMHI-RCA4) and estimated ensemble mean percentage change in 1 day monsoon maximum rainfall (MMR) with respect to their historic data sets for the two time periods 2010–2035 and 2036–2060 under the RCP 4.5 scenario. Ensemble mean 1 day MMR is projected to increase by 18 and 25% in 2010–2035 and 2036–2060, respectively (Figures 14a and 14b). For the period of 2010–2035, 31 urban areas located in the north-western and north-eastern India show declines (up to 27%) in 1 day MMR. On the other hand, 33 out of the total 57 are projected to experience increases in 1 day MMR in the period of 2036–2060. To estimate changes in risk for the selected time periods, we estimated 1, 2, and 3 day 100 year rainfall maxima at 100 year return period using the GEV distribution (Figures 14c–14h). During the 2010–2035 period, 1–3 day rainfall maxima at 100 year return period are projected to increase at the majority of the selected urban areas (Figure 14). Similarly, for the period 2036–2060, the majority of the urban areas are projected to experience increases in 1, 2, and 3 day rainfall maxima at 100 year MMR (Figures 14d, 14f, and 14h). Our results show that despite spatial variability, the majority of the urban areas are projected to experience substantial increases in storm water design storms under the projected future climate. The number of urban areas with significant increases in rainfall maxima under the projected future climate is far larger than the number that experienced significant changes in the historic climate (1901–2010). These results

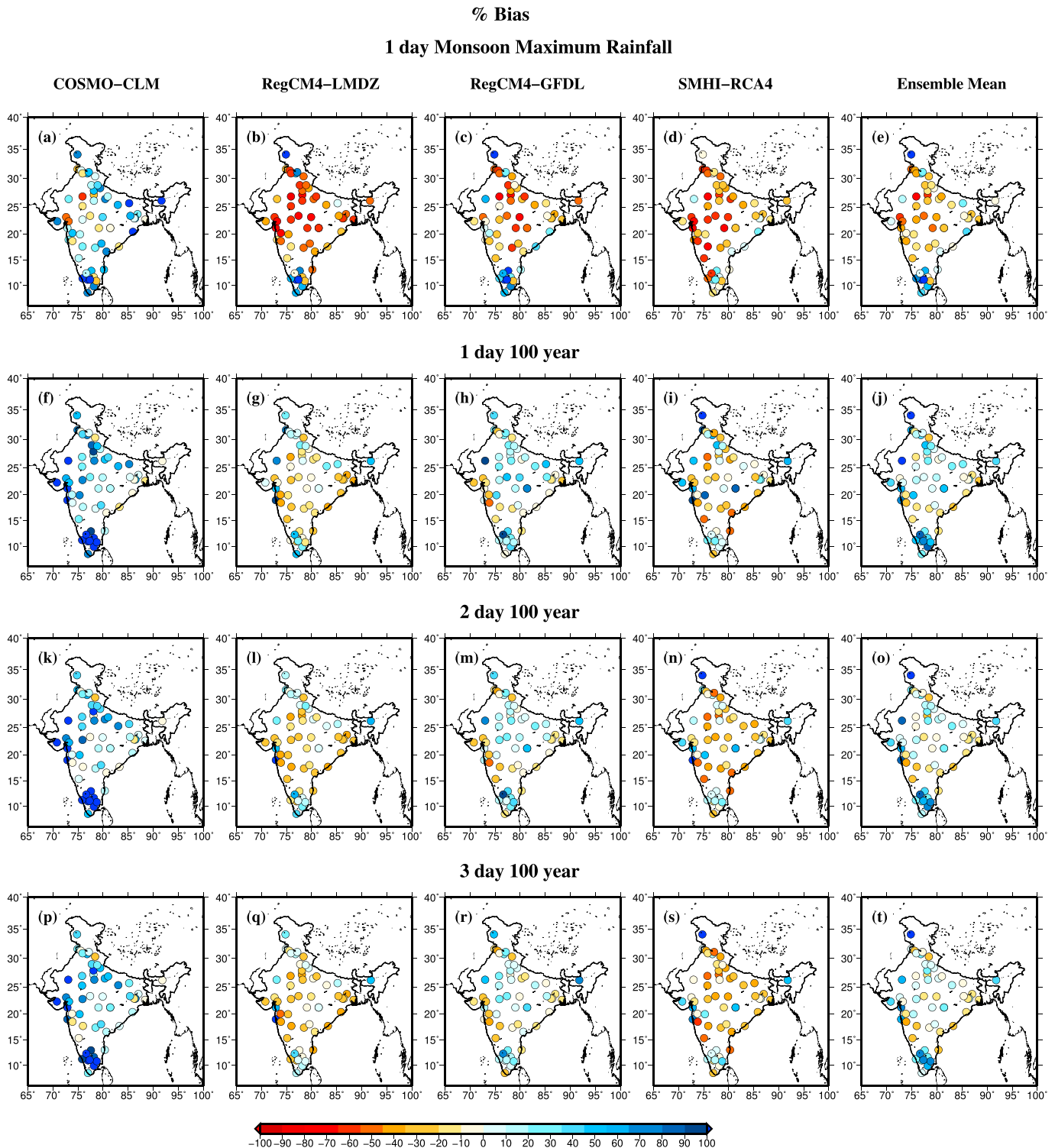


Figure 13. (a–e) Percentage bias in 1 day monsoon maximum rainfall in RCMs and their ensemble mean with respect to the observed (IMD) data sets, (f–j) same as Figures 13a–13e but for 1 day 100 year MMR, (k–o) same as Figures 13f–13j but for 2 day 100 year MMR, and (p–t) same as Figures 13f–13j but for 3 day 100 year MMR. Bias was estimated for the period of 1950–2005.

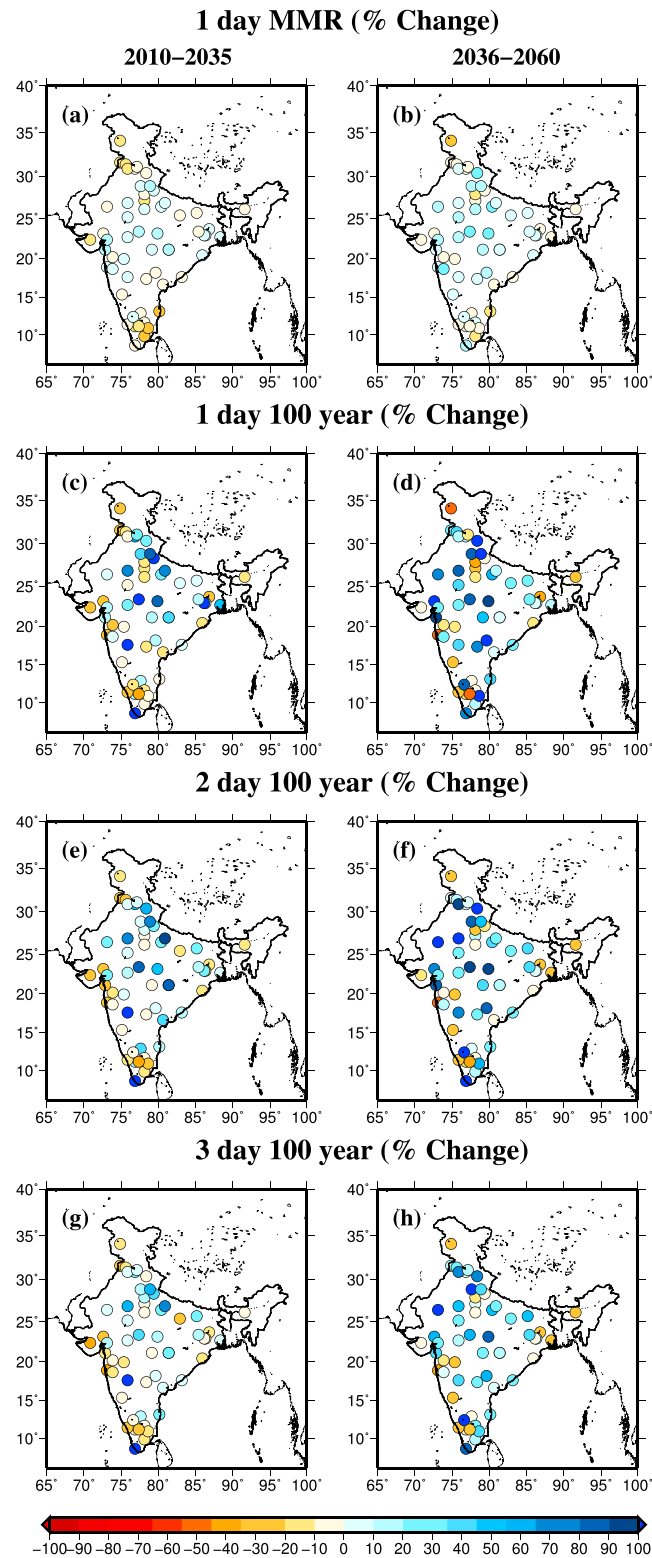


Figure 14. (a–b) Ensemble mean percentage change in 1 day monsoon maximum rainfall with respect to the historic period (1961–1990), (c–d) same as Figures 14a–14b but for 1 day 100 year MMR, (e–f) same as Figures 14c–14d but for 2 day 100 year MMR, and (g–h) same as Figures 14e–14f but for 3 day 100 year MMR. Ensemble mean changes were estimated using the data from the three regional climate models (COSMO-CLM, RegCM4-LMDZ, and SMHI-RCA4) for the two periods: 2010–2035 and 2036–2060.

are consistent with the findings of *Rao et al.* [2014] who showed using the PRECIS model that extreme rainfall intensity is projected to increase significantly over the central part of India. However, one should be cautious about uncertainty associated with extreme rainfall over the Indian monsoon region [Turner and Slingo, 2009]. Our results are based on the three RCMs which participated under the CORDEX-South Asia program. Considering uncertainty in rainfall projections, results from multiple RCMs may provide better confidence.

4. Conclusions

We examined long-term changes in extreme rainfall over the major urban areas in India to understand potential role(s) of climate variability, climate change, and increased urbanization. Using the high resolution gridded daily rainfall data, we estimated time-varying trends in extreme rainfall at multiple durations. Moreover, to evaluate changes in urban storm water design storms we estimated rainfall maxima at 1–3 day durations using the GEV distribution based on the L-moment approach. We used the recently developed dynamically downscaled projections to evaluate skills of the regional climate models in simulating extreme rainfall over the urban areas. Using the three regional climate models that participated in the CORDEX-South Asia program, changes in the monsoon maximum rainfall and the urban storm water design under the projected future climate were evaluated. Based on our findings the following conclusions can be made:

Between 1901 and 2010, only four urban areas show a significant increasing trend (p -value < 0.05) in frequency of extreme rainfall events during the monsoon season. *Kishtawal et al.* [2010] found significantly increasing trend in the frequency of heavy rainfall events over urban regions during the same season and attributed increases to rapid urbanization and urban heat island effect (UHI) [Marshall Shepherd et al., 2002; Shepherd and Burian, 2003]. Disagreement of our results with the findings of *Kishtawal et al.* [2010] can be attributed to the different analysis approach as they used fixed thresholds to identify heavy rainfall. Moreover, they considered population density as the measure of urbanization, while we considered paired urban and non-urban regions based on the satellite derived urban extents. In addition, urban areas located in the regions of high population density show significant declines in rainfall extremes during the period of 1901–2010, which highlights a potential role of a large scale climate variability rather than the localized effects driven by urbanization. For instance, the Gangetic Plain region, which is one of the most populated regions in the world, experienced significant declines in rainfall extremes that may be associated with the potential role of atmospheric aerosols as reported by *Bollasina et al.* [2011]. We also observe time-varying trends in the selected rainfall indices and found that only a few out of the total 57 urban areas experienced significant increases in the extreme rainfall indices for different periods.

We further noticed that mean and distribution of pooled MMR, R-5, R-FREQ, and H-NH did not change significantly (p -value > 0.05) from the pre- to post-1955 periods. We found that at the majority of urban areas rainfall maxima of 1–10 day durations at 100 year return period did not change significantly (p -value < 0.05) during the post-1955 period. Moreover, the number of urban areas with significant increases and declines are similar, which highlights that there is no one directional change in the extreme rainfall indices. Increased flooding events in the urban areas may not be related to climate change rather these may be associated to the sizing of stormwater drainage systems. Similarly, we did not observe any significant changes ($p > 0.05$) in pooled mean and distribution of the extreme rainfall indices for the pre- and post-1983 periods revealing a weaker role of urbanization on rainfall extremes in the major urban areas in India. Previous studies showed higher rainfall in urban areas as compared to their corresponding non-urban areas. For example, *Marshall Shepherd et al.* [2002] used the TRMM data and observed UHI induced rainfall. *Ganda and Midya* [2012] used long-term data from the Indian Institute of Tropical Meteorology (IITM) and found that some subdivisions show higher increases in the monsoon rainfall rate than their corresponding urban areas and they associated it with incapability of anthropogenic volatile compounds to affect the trends. However, our analysis based on the satellite rainfall data for the urban and paired non-urban areas did not show significant differences in magnitudes of the monsoon maximum rainfall highlighting an insignificant role of urbanization on the modification of rainfall extremes as suggested by *Kishtawal et al.* [2010].

The CORDEX-RCMs showed a significant bias in the monsoon maximum rainfall and rainfall maxima at 100 year return period at majority of urban areas. Moreover, most of the models are not able to simulate rainfall maxima within a threshold of $\pm 10\%$ bias that can be considered appropriate for storm water design purpose at majority of the selected urban areas. This deficiency in the RCMs in simulating extreme rainfall over urban

areas can be associated with the model parameterization [Gutowski *et al.*, 2010] and spatial and temporal resolution of the models [Wehner *et al.*, 2010; Tripathi and Dominguez, 2013]. Therefore, to simulate rainfall extremes at urban areas, models need better spatial and temporal resolutions [Mishra *et al.*, 2012], which is important to capture runoff response from urban areas and spatial variability associated with short-duration rainfall extremes in urban areas [Berne *et al.*, 2004].

Despite models show bias in simulating observed precipitation maxima, they may provide valuable information on changes in extreme precipitation events under the projected future climate [Knutti and Sedlacek, 2012]. Substantial increases in extreme rainfall over the urban areas are projected by the RCMs that participated in CORDEX-South Asia. For all the two selected time periods (2010–2035 and 2036–2060), ensemble mean 1 day MMR and rainfall maxima at 1–3 day durations at 100 year return period is projected to increase significantly under the projected future climate at majority of urban areas in India. Moreover, the number of urban areas with significant increases in rainfall maxima under the projected future climate is far larger than the number that experienced significant changes in the historic climate (1901–2010) warranting careful attention for urban storm water infrastructure planning and management. These results are consistent with the findings of Rao *et al.* [2014] who showed that extreme rainfall intensity is projected to increase significantly over the central part of India. Since our results are based on only three RCMs which participated under the CORDEX-South Asia program, considering uncertainty in rainfall projections, results from multiple RCMs may provide better confidence [Mishra *et al.*, 2014]. Moreover, considering the importance of urban areas in climate change impacts mitigation, observation stations with an appropriate temporal resolution in urban areas need to be increased to better understand the impacts of climate variability, climate change, and urbanization.

Acknowledgments

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